SELF-PRESSURIZATION BEHAVIOR IN INTEGRATED REACTORS

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ABSTRACT

This paper describes the transient performance of an integral self-pressurized reactor system, when a partial reduction in the SG removal power, without control or safety actions, is assumed. CAREM reactor is taken as a reference. The thermalhydraulic system code RELAP has been used for the analysis.

A special effort has been done in order to model 3-D flow paths by a 1-D code, specially within the reactor dome, that constitutes a large volume where flow paths are not well-defined. A detailed nodalization is developed, in order to allow the movement of the fluid and "fictitiously" reproduce fluid movements because of natural convection and thermal losses. Also a simpler nodalization, with a unique hydraulic node to simulate the reactor dome, is used.

A parametric study is performed in order to analyze dependence of pressure evolution with relevant factors that govern the dome dynamic behavior, regarding steam condensation on structures. The results obtained with both nodalizations are compared. An important feedback of the whole primary system on the pressure evolution has been characterized from the performed analysis.

I. INTRODUCTION

In Integral Self-Pressurized Reactors as CAREM reactor, the liquid is in thermal equilibrium with the steam in the reactor dome, that is the water of the primary circuit must be coupled thermodynamically with the steam in the dome; this condition yields an excellent self-control. But this condition should be guaranteed for pressure being controllable.

The particular behavior of this reactor differs from "standard reactors". In PWR reactors pressure is controlled by the action of heaters and showers in a pressurizer, BWR have a continuous controlled steam extraction. In CAREM-concept reactors, there is no active system for controlling pressure. This can only be controlled by thermal imbalance within the primary loop. Therefore, the intrinsic dynamics of heat and mass transfer between phases and structures becomes important because it "rules" the pressure evolution. During pressurization transients, such as loss of heat sink or reactivity insertion, the maximum reached pressure depends mainly on factors related with this phenomenology. Pressure dependence with these factors is studied in this work.

In this paper, the reactor CAREM-25 [1] [2] is taken as reference. As an integral reactor, the whole primary system is inside the Reactor Pressure Vessel (RPV). Cooling is by natural circulation; no primary pumps are needed. A diagram of this reactor is shown in Figure 1.

A steam dome is located inside the upper zone of the pressure vessel. The coolant water leaves the reactor core into the chimney, confined all along by a barrel. Then, the coolant goes to the outer annular volume through barrel windows and enters into the steam generator (SG). The circuit is closed through the down comer and lower plenum.

The control and safety rods are driven by hydraulic device, the Hydraulic Control Rod Drive System (HCRDS), that is located in the steam dome. A subcooled water flow is provided to operate this mechanism, acting as an important heat sink in the steam dome.

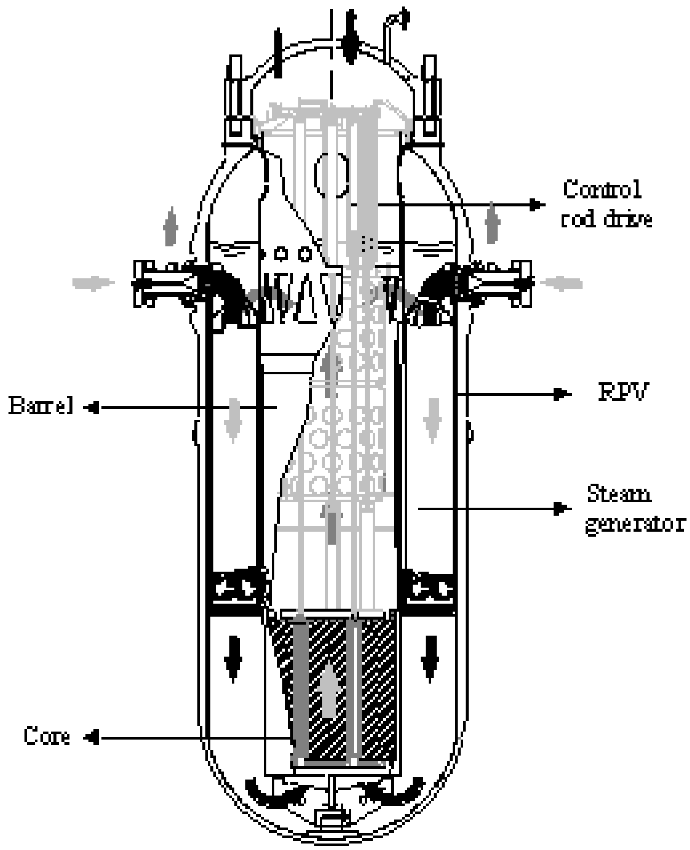

Figure 1: Diagram of CAREM-25 primary system

This design is a pressurized water reactor, but there are properties of a boiling water reactor too, as some boiling does occur within the reactor core.

Improving the quality of code predictions is connected with an increase of effectiveness of nuclear plants engineered safety features and, eventually, leads to cost reductions through better design. These activities could also contribute to the determination of a uniform basis on which to assess the consequences of reactor system failures in Nuclear Power Plants.

II. ADOPTED NODALIZATION

A simplified nodalization of primary system was developed; this is shown in Figure 2. RPV structures are only modeled in the dome volume.

Reactor dome is a relatively big volume, where flow paths are not clearly defined. When using 1-D codes several problems appear, because they are developed to reproduce well-defined flow paths. One approach is averaging liquid and steam properties within this space. This is achieved using a unique hydraulic volume to simulate the reactor dome, as s hown in Figure 2.

Nevertheless, this nodalization could not be conservative when modeling the thermo dynamical coupling, as long as average properties are the approximation of instantaneous mixing.

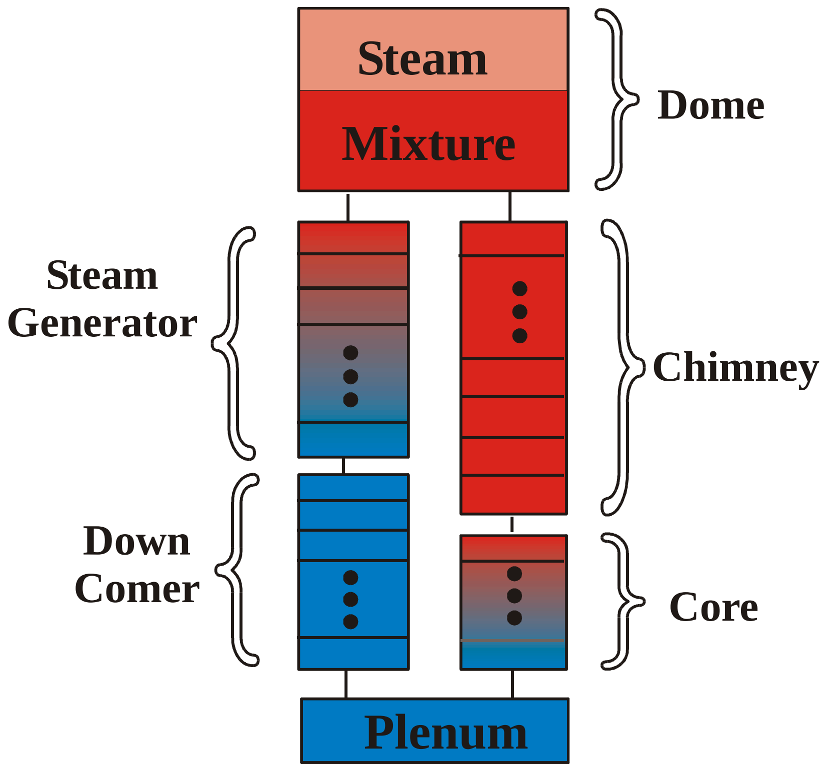

Figure 2: Primary system nodalization

A second nodalization was developed, with a special effort within the reactor dome, in order to approximate 3-D flow paths. The rest of the circuit was not modified. Figure 3 shows the dome nodalization.

Dome is divided in two spaces, separated by the barrel: outer and inner spaces; which are communicated through barrel structure by means of the mentioned windows in the liquid zone and holes in the steam zone. The HCRDS are located in the inner space.

The nodalization is conceived in order to allow the system to reproduce the most probable macroscopic patterns (estimated with engineering criteria) inside the whole steam space. Steam is expected to condensate on the surface of the coolest structures. These are the RPV, because of heat losses to the reactor containment, and HCRDS, since they are feed with subcooled water. For pressure being in steady state condition, the steam condensation must be compensated by an equivalent steam flow. This steam is created in the core, producing a void fraction all along the chimney, from the core outlet to the dome entrance. So steam is expected to flow upward, through inner spaces, and downward near the cooler surfaces, while condensing on them. In the nodalization, these flow patterns are allowed by means of differentiated volumes in these regions: for example, volumes 312 to 318 represent the inner spaces inside the barrel, not in contact with HCRDS structures; volumes 324 represent the space near the walls of HCRDS. The same criterion is applied in the barrel outer space and the upper zone, which are in contact with RPV. Volumes 314 and 360 are connected through a junction representing the barrel holes.

RPV structures are modeled as shown in the Figure 3; they are separated in zones with different thickness, because of RELAP input requirements, and because RELAP code assumes one-dimensional heat conduction with negligible linear heat flow, so axial heat conduction through walls is not modeled.

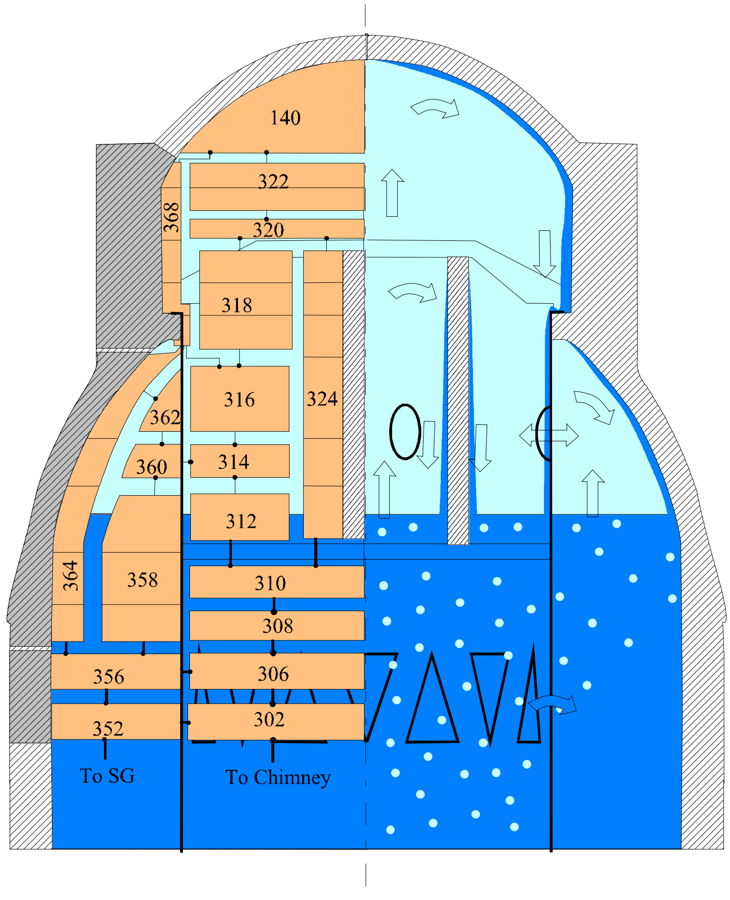

Figure 3: Steam dome nodalization

III. LOSS OF HEAT SINK DESCRIPTION

A partial reduction in the SG removal power is simulated. In order to allow the analysis of the intrinsic reactor behavior, despite on the “actual” reactor behavior, fluid-neutronic coupling is avoided and neither control nor safety actions are included. To obtain comparative results, energy imbalance must be equal in all the simulations. This is achieved modeling the heat transferred to the coolant in the core and removed in the S.G. as boundary conditions. In RELAP, this is implemented by means of a “fictitious” structure with a reduced heat capacity. The initial condition is a stationary state, at 100 % of full power, and the S.G. heat removal rate is decreased to 10 % in a 40 s ramp (Figure 4). The same ramp is applied to the core with a 20 s delay.

When the transient begins, fluid temperature raises in the S.G. outlet. Then, flow begins to decrease due to the loss of buoyancy force. At the same time, the coolant expands and the system pressure rises. Therefore, pressure evolution constitutes a representative response functional in assessing the whole system from the safety point of view, and will be the main parameter to be analyzed.

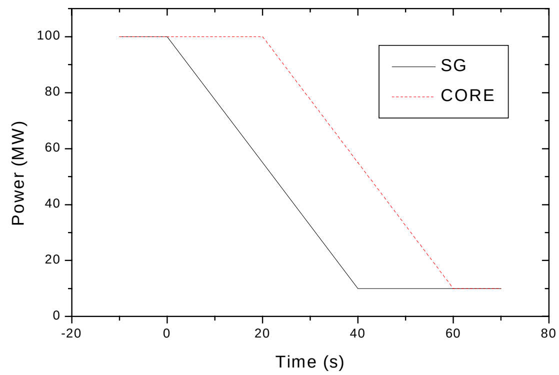

Figure 4: Core and SG power evolution

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The major goal of this work is to study the main characteristics of the physical phenomenologies that occur in the dome. Two extreme cases are possible: Thermodynamic equilibrium between water and steam, and complete thermal decoupling between water and steam in the dome. First case could be approached by means of a heat sink in the steam dome. In CAREM reactor, this is provided by the HCRDS and heat losses through the RPV walls. The second case results when no heat transfer between phases is allowed, the consequence is an adiabatic compression.

IV. METHODOLOGY

In order to understand the involved phenomenology, a parametric study is performed to analyze the influence of different factors in the dynamic behavior during the pressurization transient.

The most important parameters to be studied are the heat structures in the dome, a heat sink within the steam and the subcooled void fraction generated in the core.

Due to the complexity of the system and to get a better understanding of the phenomenology related with the different factors, the analysis is done gradually, grouped in "cases", increasing the system complexity. The two proposed nodalizations, simplified and detailed one, are studied in each case, in order to understand the approximations done in both nodalizations to model the phenomenologies related with these factors.

Case 1: Base Case. In this case, no heat sink or heat structures in the dome are modeled. Subcooled boiling is inhibited by means of fictitiously increasing the heat transfer area on the core; by this way heat flux is low enough to avoid ONB (Onset of nucleate boiling), so no subcooled void fraction is allowed in the chimney.

Case 2: Structures. During the pressurization transient, as the steam is over heated, condensation occurs on the structures, until they reach thermal equilibrium. In order to study the impact of this phenomenon on pressure evolution, dome structures are added to the base case (Case 1). No heat losses are included in this case.

Case 3: Heat Sink**.** In this case, a heat sink in the steam dome is modeled by means of the HCRDS heat removal and thermal losses through the RPV walls. These are included as a boundary condition on the external side of the respective structures; with a fixed heat transfer coefficient and an external temperature.

Case 4: Subcooled void fraction. This is an important factor during the transient. When pressure rises, the subcooled void fraction all along the chimney is collapsed. This contributes to limit the maximum pressure, because of the big liquid/vapor interface area of bubbles.

The subcooled void fraction is achieved by means of reducing the heat transfer area in the core, in order to approximate the design value of CAREM-25.

V. RESULTS

Base Case. The results obtained with the two nodalizations (detailed and simplified) are compared in Figure 5 and 6. As can be seen, the difference between both cases is neglectable.

In this case the system is almost completely uncoupled: steam zone remains over-heated because the heat transfer coefficient and area between both phases are very small. So the system remains at high pressure in this transient, and it cannot be reduced by a new thermal imbalance between core and SG, so the pressure is difficult to control.

Structures. Results obtained with both nodalizations, shows that maximum reached pressure is lower than the base case, because of structures thermal capacity.

Comparing both nodalizations results, maximum pressure in the simplified one is higher than in the detailed one. In the detailed nodalization, the heat transfer coefficient is greater than simplified case. (~30000 vs ~3000). This is probably because in the first one, steam movement is allowed and the heat transfer to structures is increased. This can be observed in structure connected to volume 368, because it is entirely in contact with steam phase. In the other hand, in simplified nodalization, instead, the steam is stagnant.

At medium term (after 80 seconds approximately), this tendency is inverted: In detailed nodalization pressure decreases at lower rate than simplified one. This is because in the later, the whole dome structure is in contact with both phases, steam and liquid. Since the liquid is always at lower temperature, there is a continuous heat flux from the structure to the liquid phase, and this causes the structure to cool faster; then, the wall temperature becomes lower than the saturation temperature. As long as this is the same structure in contact with the steam, this causes a heat flux from the steam to the structure. In other words, on the simplified nodalization the structure acts as a by-pass between both phases, and this causes the system to reach equilibrium faster. In detailed nodalization instead, both phases are in contact with different structures nodes. As long as axial heat conduction through walls is neglected in RELAP5, the system is uncoupled and therefore, if this nodalization were representative of real system, would be difficult to control.

The difference between initial and final pressure depends on the total energy transferred and accumulated into the system and the initial conditions, this means it doesn't depend on condensation and boiling rates in the dome, so final pressure must be equal in a very long term.

Dome heat sink. A continuous steam condensation is produced during steady state condition. For pressure to be in equilibrium, an equivalent steam flow must be provided from the liquid zone, in order to compensate the condensation. As in this case subcooled boiling is inhibited (see section IV), there is only saturated void fraction. That is produced from the upper zone of the chimney and downward, when saturation temperature equals fluid temperature, due to the hydrodynamic pressure gradient with height.

Simplified nodalization has still an over-estimation of maximum pressure, comparatively with detailed one, but they are much closer than in the previous case. This means, in case of existing steam condensation, pressure evolution not only becomes more controllable, but also more predictable with simpler models.

During the transient, all the liquid remains in subcooled condition, as long as the saturation temperature rises with pressure. After the maximum is reached, pressure drops until saturation condition in the chimney is reached (Figure 6), then void fraction re-appears and reposition of condensed steam in the dome is re-established.

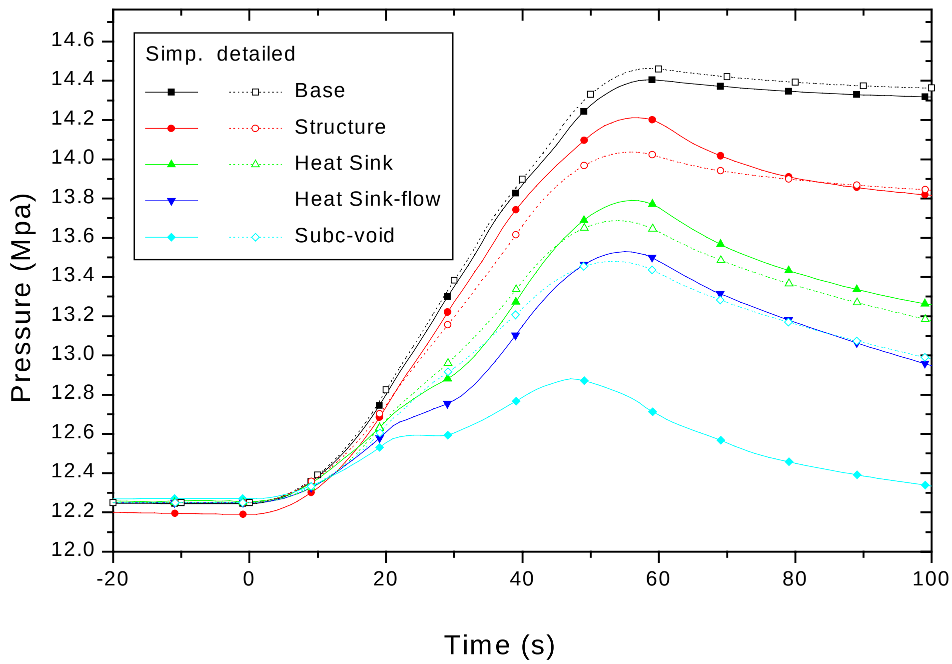

Figure 5: Pressure evolutions - short term

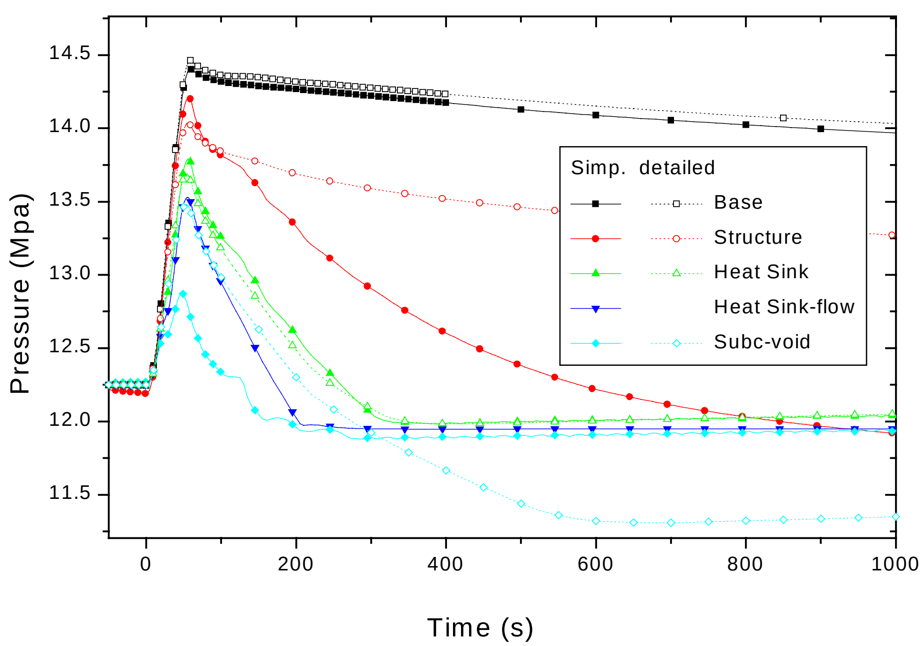

Figure 6: Pressure evolutions - Long term

In case of simplified nodalization, important oscillations had been found, mainly on dome power extraction; it has been found that these oscillations are originated in heat transfer coefficients. To avoid them, an alternative boundary condition was proposed: a constant steam bleed is imposed from the steam zone and the same flow is returned to the liquid zone in the dome, as saturated liquid. The flow fulfills the following condition:

$$W_c = \frac{Q_c}{h_{fg}} \tag{1}$$

Where Q_c is the imposed total power extracted from the dome, h_{fg} is the heat of vaporization. With this condition, oscillations disappear, as can be seen in Figure 7. However pressure evolution has a lower peak, as a consequence of this modeling approach,

Figure 5; so this condition is not conservative. This is because, in previous approach, when water level rises, parts of dome structures are covered with water, and the heat interchange area to the steam reduces. This causes a reduction on the power extraction from steam. With the constant bleed approach, this phenomenon is not reproduced.

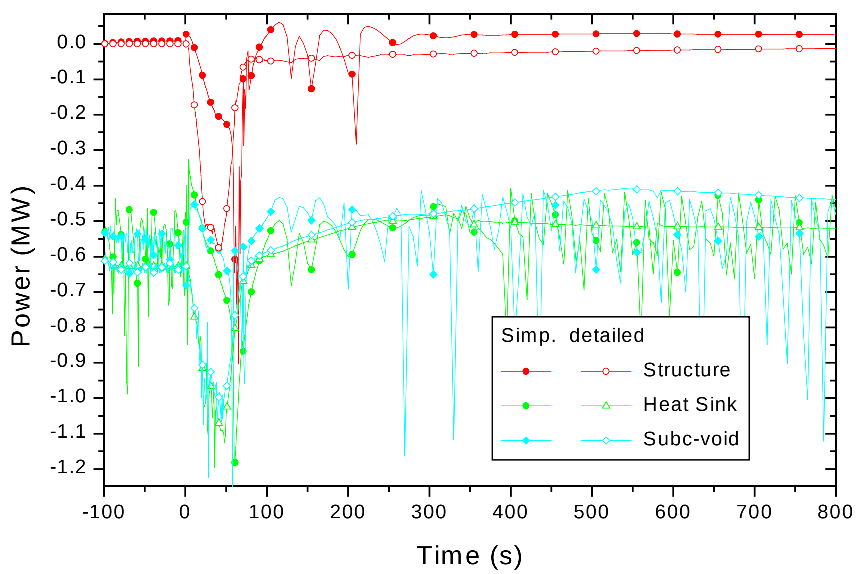

Figure 7: Transferred power from the structures

Subcooled void fraction. Conditions required to allow subcooled void fraction to exist are:

- Wall temperature must be higher than fluid saturation temperature.
- Fluid enthalpy must be higher than the "critical enthalpy".

$$T_c = T_{f,sat} - \frac{Nu}{455} \qquad ; \qquad Nu = \frac{q''_f\, D}{k_f} \tag{2}$$

The apparition of subcooled void fraction in the core changes the steady state of both nodalizations. Now, void fraction generated in the core exceeds the amount condensated on structures, and therefore the difference must condensate within the chimney and dome liquid, in order to keep pressure at steady state.

Mass transfer rate at the vapor/liquid interface due to condensation can be written as:

$$Wc = \frac{h_{if} A_i \left(T_s - T_f\right)}{h_{fg}} = \frac{H_{if} \Delta T_{sf}}{h_{fg}} \tag{3}$$

h_{if} is the interfacial heat transfer coefficient, A_i is the interfacial area between phases, T_s is the saturation temperature, T_f is the liquid temperature, $H_{if} = h_{if}*A_i$ the global interfacial heat transfer coefficient.

Detailed and simplified nodalizations behave differently when subcooled boiling is present. For comparison between both nodalizations, the primary coolant flow was "tuned" to nominal value: 410 kg/s.

In the detailed nodalization, liquid phase above volumes 306 and 356 (Figure 3), cannot be recirculated and therefore is stratified and in near saturation. These volumes don't participate in the mass transfer because ΔT_{sf} is neglectable, eq. (3). In order to the system been able to condensate the mentioned extra-void fraction, and to reduce the subcooled void fraction production (according to equation (2)) subcooling of approximately 8 ^{o}C is established in the "hot leg".

In the simplified nodalization, the subcooling is around 2 ^{o}C, lower than in the detailed one. As it has been said, dome simplified nodalization is an approximation of instantaneous mixing. So, as a difference of detailed nodalization, there are not stratified zones and all the liquid participates in the condensation process. A unique interfacial heat transfer coefficient is used in the whole volume, and is observed that is greater than the corresponding to non-stratified volumes in detailed case. As a consequence, steam quality in the chimney is higher in the simplified nodalization.

During transient, when increasing pressure, the first effect taking place is T_s and ΔT_{sf} increase, so Wc is tends to rise, according to equation (3) (neglecting changes in H_{if} and h_{fg} in this stage)

$$\frac{\partial Wc}{\partial t} \approx \frac{H_{if}}{h_{fg}} \frac{\partial \Delta T_{sf}}{\partial t} \tag{4}$$

As it can be seen, if H_{if} is higher, this effect on Wc is magnified. Shortly after, H_{if} decreases because bubbles collapse in chimney and dome. In simplified nodalization, calculated H_{if} in the dome is higher than the average in detailed one. When pressure rises, H_{if} is still important, so Wc increases because ΔT_{sf} effect, and pressure rise is limited. This explains the difference between both nodalizations.

At long terms, after the peak of pressure, according to eq. (2), saturation temperature must drop until void fraction generation in the core is re-establish to allow reposition of the steam that is condensed. So, according to eq. (2):

$$T_{f,sat} = T_{f,core} + \frac{q''_f\, D}{455 k_f} \tag{5}$$

As q'' is reduced, $T_{f,sat}$ will be closer to $T_{f,core}$ than in initial condition. This is more appreciable in detailed nodalization, where initial liquid subcooling is higher.

VI. CONCLUSIONS

For self-stabilization of the system the water of the primary circuit must be coupled thermodynamically to the steam in the dome. The totally decoupled system becomes un-controllable in case of pressure rise transients. Ways to thermodynamically coupling the water to the steam are heat conduction, boiling and condensation. A heat sink within the steam dome forces thermodynamic equilibrium between water and steam. This condition yields excellent self-control. Without the heat sink, thermal coupling is not guaranteed during with pressure rises transients.

A detailed nodalization is developed, in order to model 3-D flow paths by a 1-D code, specially within the reactor dome. This is compared with a simpler nodalization, with a unique hydraulic node to simulate the reactor dome, during a pressurization transient originated in a partial removal power reduction.

It is observed, in the detailed nodalization, that steam movement increases heat exchange with structures. In simplified nodalization, structure acts as a by pass between both phases, as long as the same structure temperature condition is imposed to both of them.

When a heat sink in the dome is included, thermal equilibrium is forced, the effect of the different structure modeling is minimized and both nodalizations behave similarly.

When subcooled boiling in the core occurs, void fraction generation exceeds the amount condensated on structures, and therefore the difference must condensate within chimney and dome liquid. In detailed nodalization, some fluid is observed to be stagnant, that don't participate in heat interchange. Simplified nodalization is an approximation of instantaneous mixing in the dome, and this maximizes heat transfer between phases in the mixture zone. Also a higher interfacial heat transfer coefficient is predicted by the code. Therefore, the result is a relative over-prediction of subcooled void fraction in the steady state, respect to detailed nodalization, and more limited pressure rises.

Some dependence on results with code nodalization was verified. Specifics phenomenologies could not be reproduced if nodalization is not properly developed, and this produces an important user-effect in "best-estimates" codes. Qualification of nodalization becomes a vital element, jointly with models improvements. The adequate assessment and validation of both factors could only be certain by means of experimental facilities.

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